Development of a Boron Neutron Capture Therapy Treatment Planning System Based on MeVisLab

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Abstract

Boron Neutron Capture Therapy (BNCT) is a targeted cancer therapy technique that combines radiotherapy and chemotherapy, whose Treatment Planning System (TPS) performance influences treatment plan formulation and consequently therapeutic efficacy. This study develops a modular BNCT treatment planning system based on the MeVisLab medical image processing platform, aiming to achieve automation, precision, and visualization in the treatment planning process. The system integrates fundamental functional modules including medical image processing, dose calculation, and dose visualization, capable of efficiently processing medical imaging data such as CT and MRI, and performs neutron dose distribution calculations based on the Monte Carlo simulation program OpenMC. Leveraging OpenMC's efficient particle transport simulation capabilities, the system can accurately calculate dose distributions arising from nuclear reactions between particles and boron-10 in tumor tissues, ensuring dose calculation accuracy. Furthermore, the system employs a modular design architecture, which enhances flexibility for algorithm extension and user customization, and provides an intuitive three-dimensional visualization interface to facilitate treatment plan design and optimization for clinicians. The design and implementation of this system provides reliable technical support for precision therapy in BNCT.

Full Text

Development of a MeVisLab-Based System for Boron Neutron Capture Therapy Treatment Planning

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Abstract

Boron Neutron Capture Therapy (BNCT) is a targeted cancer treatment modality that combines radiotherapy and chemotherapy, where the performance of the Treatment Planning System (TPS) directly influences treatment plan quality and therapeutic outcomes. This study presents the development of a modular BNCT treatment planning system based on the MeVisLab medical imaging platform, aiming to achieve automation, precision, and visualization in treatment planning. The system integrates fundamental functional modules for medical image processing, dose calculation, and dose visualization, enabling efficient processing of CT and MRI data while performing neutron dose distribution calculations through Monte Carlo simulations using OpenMC. Leveraging OpenMC's high-performance particle transport capabilities, the system accurately computes dose distributions generated by neutron interactions with boron-10 nuclei in tumor tissues, ensuring calculation accuracy. The modular design architecture facilitates flexible algorithm extension and customizable user operations, while providing an intuitive three-dimensional visualization interface to assist physicians in treatment plan design and optimization. This system provides reliable technical support for precise BNCT treatment.

Keywords: Boron Neutron Capture Therapy, Treatment Planning System, MeVisLab, OpenMC

Boron Neutron Capture Therapy (BNCT) represents a binary radiotherapy approach with strong targeting capability and high linear energy transfer [1]. The principle involves injecting boron-10 (^{10}B)-labeled targeting molecules into the patient, which accumulate specifically within tumor tissue. Subsequent irradiation with an external beam of low-energy epithermal neutrons induces the $^{10}\mathrm{B}(n,\alpha)^{7}\mathrm{Li}$ reaction within tumor cells, releasing α particles and ^{7}Li nuclei with ranges of approximately 10 μm. This enables precise cell-level destruction

of cancer cells while minimizing damage to surrounding healthy tissue. The fundamental reaction is expressed as:

$$^{10}\mathrm{B} + n \rightarrow ^{7}\mathrm{Li} + \alpha + 2.31\,\mathrm{MeV}$$

The Treatment Planning System (TPS) constitutes a critical component in BNCT, as accurate dose calculation enables physicists and physicians to design treatment plans that enhance irradiation precision in tumor regions while maximizing protection of adjacent normal tissues. Throughout the evolution of BNCT-TPS technology, Monte Carlo simulation algorithm optimization and voxel model construction methodologies have formed the core development trajectory [4]. Early foundational platforms included SERA [5] and NCTPlan [6], developed by Harvard University and Montana State University respectively. SERA established a three-dimensional model comprising 11,025 voxels $(21\$\times21\times25) and implemented dose calculations for reactor neutron sources using MCNP-4B, while NCTPlan enhanced computational efficiency through its proprietary SeraMC engine, becoming one$ grid merging techniques. Tsukuba University's TsukubaPlan [9] extended multi-particle joint simulation capabilities based on the PHITS code, supporting combined neutron/photon/heavy ion therapy modes. In the commercial domain, Sumitomo Heavy Industries' NeuCure [10] achieved synergistic image processing and dose visualization through integration with the RayStation platform, while China Boron Medical's NeuMANTA [11] employed the proprietary COMPASS Monte Carlo engine specifically designed for BNCT dose calculations, enabling rapid and accurate dose computation. Table 1 summarizes the characteristics of current mainstream BNCT-TPS platforms.

This study constructs a BNCT treatment planning system integrating multi-modal image processing, target delineation, neutron transport simulation, and three-dimensional dose visualization, built upon the MeVisLab medical imaging platform and OpenMC Monte Carlo simulation engine. Through modular architecture design, the system achieves precise control of the entire BNCT treatment workflow. The DICOM standard interface enables spatial registration of CT/MRI multi-modal data, while parallel computing optimization strategies in the OpenMC neutron transport engine achieve clinically acceptable computational efficiency while maintaining spatial resolution (computational data demonstrate that OpenMC and MCNPX exhibit less than $\pm$0.59% error in total neutron flux distribution calculations using the Snyder model). The modular architecture supports extension with DICOM-RT dose data interfaces, providing a systematic solution for BNCT clinical translation that combines geometric flexibility (spatial resolution can be set according to medical image resolution), high-performance computation, and strong extensibility.

1.1 MeVisLab Medical Image Processing Platform

MeVisLab, developed by German company MeVis Medical Solutions AG, is a professional medical image processing and visualization platform widely applied

in medical image analysis, computer-aided diagnosis (CAD), and radiotherapy treatment planning system development. The platform provides comprehensive image processing tools and a modular programming environment supporting fusion and processing of multi-modal medical imaging data including CT, MRI, and PET. Its powerful visualization capabilities and flexible modular design enable developers to rapidly construct complex medical image processing pipelines and integrate advanced algorithms for target delineation, registration, and visualization. Notably, MeVisLab offers Python/C++ hybrid programming interfaces based on the Qt framework, supporting user-defined module development for specific research requirements. This feature demonstrates significant advantages in cutting-edge domains such as intelligent radiotherapy target delineation and multi-modal image-guided surgery.

1.2 OpenMC Monte Carlo Simulation Code

OpenMC [12] is an open-source Monte Carlo particle transport simulation tool specifically designed for neutron and photon transport calculations. Implemented with Python, OpenMC delivers high computational performance and flexible extensibility, enabling distributed computing across cluster nodes through hybrid MPI/OpenMP parallel architecture. The code has found extensive applications in nuclear reactor physics, radiation shielding design, and medical physics. OpenMC supports multiple geometry description formats (including CSG and DAGMC) for handling complex geometric structures and provides comprehensive physics models and nuclear data libraries to ensure simulation accuracy.

2 System Architecture and Implementation

Figure 1 [Figure 1: see original paper] illustrates the workflow of the BNCT treatment planning system, which comprises medical image import, image registration, target delineation, voxel model construction, dose calculation, beam configuration, and dose visualization functions. Image preprocessing, delineation, parameter configuration, and dose visualization are implemented using the MeVisLab medical image processing software, while dose calculations are performed by the OpenMC Monte Carlo simulation program.

The entire system is implemented through modular programming, with modules defining various interface types to enable data input and output. Figure 2 [Figure 2: see original paper] presents the user interface, designed using the MeVisLab Definition Language (MDL) to facilitate rapid and convenient utilization of system functions for efficient treatment planning by physicians and physicists.

2.1 Medical Image Registration The system provides configurable medical image registration functionality. As shown in Figure 3 [Figure 3: see original paper], the core MERIT [13] module supports affine, rigid, and non-rigid transformations while enabling cross-modal registration. The

input layer incorporates two DirectDicomImport modules for loading template and reference DICOM images, supporting patient coordinate system alignment. Reference_Image_Import handles reference image import, while Template_Image_Import manages template image import. During registration, the template image adjusts its position and morphology according to the reference image, which remains unchanged.

Registration results are visualized through the RegistrationManual module, providing difference overlays, local ROI magnification, and deformation field grid displays. The SoRenderArea module renders multi-resolution NMI error curves in real-time, dynamically reflecting registration convergence status (Gill-Murray-Wright criterion). Figure 5 [Figure 5: see original paper] visualizes registration errors during the process. Additionally, the SoDiagram2D module monitors iteration parameters (such as similarity scores), while the StylePalette module adjusts visualization styles. MERIT's plugin framework supports extension with non-linear deformation algorithms (such as elastic filtering), and combined with mask image input and input validity verification, ensures robustness in complex scenarios.

2.2 Target Delineation Target delineation constitutes a critical step in radiotherapy planning, with its accuracy directly affecting dose calculation precision. The system provides both manual and semi-automatic delineation modes, implemented as shown in Figure 5(a). Manual delineation is based on the SoCSOLiveWire module, employing dynamic edge detection algorithms that optimize energy functions (including gray-level gradients and curvature constraints) between contour path points, enabling automatic alignment with anatomical boundaries and reducing manual errors. Semi-automatic delineation utilizes the CSOSliceInterpolator module, which implements a multi-modal interpolation algorithm: first constructing a continuous contour through cubic uniform B-spline surface functions on sparsely marked user points, then employing the Marching Cubes algorithm to scan spatial topological relationships between adjacent slices and adaptively fill missing contour data, ensuring anatomical consistency across layers. In semi-automatic mode, users need only delineate a limited number of slices to generate contours for unmarked sections, with manual adjustment capabilities for generated contours. Figure 6 [Figure 6: see original paper] demonstrates the delineation results.

Delineation results are converted into DICOM RT-compliant hierarchical structures via the CreateRTStruct module, with the RTObjectSave module generating standardized RTStructure files (containing contour geometric data, label attributes, and spatial coordinate system information) for subsequent dose calculation and plan evaluation. The result saving process is shown in Figure 5(b). The system manages delineation object lists in real-time through the csolist module, combined with the SoView2DCSOExtensibleEditor module for interactive contour editing and validation, ensuring data integrity.

2.3 Voxel Model Construction CT images fundamentally reflect tissue characteristics by measuring X-ray attenuation after penetration. Since different tissues with varying composition and density exhibit distinct X-ray absorption capabilities (e.g., strong absorption by bone, weak by fat), the transmitted X-ray intensity creates gradient variations that generate grayscale contrast images. To quantify these attenuation differences precisely, medical imaging employs the Hounsfield Unit (HU), also known as CT value, defined as:

$$\text{HU\_value} = \text{pixel\_value} \times \text{slope} + \text{intercept}$$

where pixel_value represents the grayscale value in raw CT image data typically acquired directly from device detectors, and slope and intercept are device calibration parameters for converting raw pixel values to standardized HU scales. By mapping HU values to grayscale gradients, CT images enable tissue density differentiation for identifying various human tissues.

Normal human tissue HU values are listed in Table 2 . The HU-value-based system employs a piecewise linear regression model to classify voxels into 35 material categories. For extremely low-density regions with HU $<$ -950 (e.g., air-filled cavities), air/lung tissue is defined at 10 HU intervals. Soft tissues (-100 $\leq$ HU $<$ 100) are subdivided at 20 HU intervals to match density differences of brain gray matter (\$ $35HU), whitematter($ \$25 HU), and fat (-100 to -50 HU). Bone tissue (HU $\geq$ 100) uses 50 HU intervals. The final output comprises a voxel matrix containing elemental composition, density, and spatial coordinates (Figure 7 [Figure 7: see original paper]) for Monte Carlo modeling and particle transport calculations to obtain dose distributions.

To meet dose calculation speed requirements, geometric models can be scaled to significantly improve computational efficiency with minimal accuracy loss [14]. Therefore, the system supports geometric resolution adjustment based on different accuracy requirements. For instance, a standard 512\$$\times$512$CTimagecanbescaledto64\times$\$64 during voxel model construction.

2.4 Treatment Parameter Configuration In the voxel model-based BNCT dose simulation system, users can directly configure key neutron source parameters through the visual interface (Figure 8 [Figure 8: see original paper] shows beam geometry parameter configuration), including particle numbers (determining neutron flux intensity), neutron source geometry parameters (position, incident angle, beam shape), and preset boron concentration in tumor regions. The system automatically completes radiation field modeling and dose calculation based on these inputs. In addition to neutron source parameters, users can input biological effect parameters: RBE (relative biological effectiveness factors for nitrogen or hydrogen dose) and CBE (compound biological effectiveness factor for boron neutron reaction). The system converts physical doses (D_B, D_N, D_H, D_γ) to biologically equivalent doses (Gy-Eq) based on these factors.

2.5 OpenMC Implementation The system constructs the BNCT-TPS dose calculation engine based on the OpenMC open-source Monte Carlo neutron transport framework, employing a hybrid architecture that leverages OpenMC's Python API for geometry modeling, physics process definition, and computational workflow control. A fine three-dimensional mesh is superimposed on the geometric model to tally neutron flux distributions in different spatial regions. According to ICRP Publication 116 [15], neutrons and photons are divided into different energy groups to accurately tally flux across energy intervals. Specifically, four tallies are configured: (1) total neutron flux, (2) fast neutron flux (44 energy groups), (3) thermal neutron flux (9 energy groups), and (4) photon flux (39 energy groups).

Based on OpenMC flux calculation results, the system converts flux to dose using preset boron concentrations and flux-to-dose conversion factors, generating standard RTdose files. The BNCT dose calculation formula is:

$$D_{\text{total}} = C_B \times D_{B,\text{ppm}} \times CBE_B + D_N \times RBE_N + D_H \times RBE_H + D_\gamma$$

where D_{total} is the total dose, C_B is boron concentration, $D_{B,\text{ppm}}$ is the absorbed dose from boron neutron capture reaction, D_N is fast neutron dose, D_H is hydrogen capture dose, D_γ is gamma dose, CBE_B is the compound biological effectiveness factor for boron neutron reaction, and RBE_N and RBE_H are relative biological effectiveness factors for nitrogen and hydrogen doses, respectively. The accuracy of OpenMC for BNCT dose calculations has been validated in literature [16], with maximum neutron flux calculation errors of 0.59% compared to MCNPX, which is not reiterated here.

2.6 Dose Visualization Utilizing MeVisLab's Python programming interface, this study developed a dose distribution visualization analysis module tailored to clinical TPS requirements, enabling dose distribution display as exemplified in Figure 11 [Figure 11: see original paper]. Users can interactively observe isodose curve distributions on arbitrary anatomical planes. The system can also generate Dose-Volume Histograms (DVH) by combining RTStructure and RTDose files, facilitating quantitative analysis of dose delivery to targets and normal tissues to ensure treatment plan targeting and safety, providing intuitive and reliable evaluation evidence for clinical decision-making. Figure 9 [Figure 9: see original paper] illustrates dose visualization capabilities including layered isodose contours and dose-volume histograms.

This study successfully developed a BNCT treatment planning system based on MeVisLab and OpenMC, achieving full-process integration from medical image processing through dose calculation to dose visualization. The system completed multi-modal image registration and target delineation based on the MeVisLab platform and designed a user interface; established a neutron transport and boron concentration coupled dose model using the high-performance OpenMC

Monte Carlo engine; and implemented dose visualization functionality through MeVisLab's Python interface. Future work will focus on real-time boron concentration monitoring algorithm optimization, multi-modal medical image fusion, and automatic treatment plan generation to promote clinical application and popularization of BNCT technology.

Author Contributions

YANG Xunwu was responsible for overall architecture design, medical image processing implementation, dose visualization implementation, system integration, and manuscript writing. LU Peng supervised manuscript review and revision. WANG Shengzhe designed and implemented the OpenMC Monte Carlo simulation program. ZHANG Xulei, TAN Wenwen, and WANG Liye conducted literature review and data compilation. LI Jia and LIANG Lizhen provided methodological guidance.

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Note: Figure translations are in progress. See original paper for figures.